NV-center microscopy of spin wave beams

The SEED[1] program (industry track)

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PhD topic open for applications until January 31st, 2024

1 Definition

1.1 Domain and scientific/technical context

The ongoing miniaturization of conventional electronics relying on CMOS technology is accompanied with serious heat generation, which requires alternative solutions beyond Moore's law. A key contender for future energy- efficient computing and signal processing devices is based on the manipulation of magnons or spin waves, which are the elementary excitations of magnetic materials. Magnons can be manipulated on a broad range of the microwave spectrum at both room and low temperatures, typically between 100 MHz and 300 GHz, with small footprints down to nanometers, and are therefore of interest for 5G/6G applications [1]. Besides, a wide variety of non-reciprocal effects inherent to spin dynamics offers promising opportunities for the miniaturization of analog signal processing components such as microwave isolators, circulator and directional couplers [2]. Furthermore, new functionalities are emerging from non-boolean and wave-based computing concepts, where both amplitude and phase of spin waves are considered as new degrees of freedom for encoding the information [3]. For all these reasons, spin-wave devices are now recognized as a credible beyond-CMOS technology.

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1.2 Scientific/technical challenges

Recent studies demonstrated that the propagation of spin waves can be shaped in a similar fashion to basic concepts in optics [4]. With the aim of exploring the potential of magnonic interferometry, we propose to study the spin-wave beamforming in continuous thin films either from antenna shapes, scattering sites, or non-linear excitations. We will explore near-field diffraction effects of spin waves at the nanoscale to master multibeam interference, and ultimately design miniature spin-wave interferometers.

For this purpose, we will resort to scanning NV magnetometry, a quantum technology based on nitrogen vacancies in diamond, which offer unprecedented sensitivity and spatial resolution [5]. However, research on spatially resolved spin-waves is at a very early stage, and constitutes mostly proof-of-concept measurement obtained on a home-built system at comparably low frequencies (i.e. below 3GHz). We aim to broaden the scope of measurements on a commercial instrument, and expand the field and frequency ranges for spin wave imaging at the nanoscale.

1.3 Considered methods, targeted results and impacts

The first outcome of this project will be the realization of a commercial instrument capable of imaging magnetization dynamics at the nanoscale at unprecedented frequency and applied field range. We will create a measurement scheme that simplifies the access for non-expert users, and measure devices where nanometric resolution is key to understanding the electrical performance. We expect to develop an integrated probing scheme for Qnamis commercialized NV center microscope, dedicated to the imaging of spin dynamics with 50nm spatial resolution, and operating at magnon frequencies up to the 10 GHz, and under applied external fields up to 500 mT. The identification of magnonic prototypes will be obtained through both near-field diffraction simulations as well as micromagnetic simulations. The most suitable geometries for interferometric magnonic devices will be subsequently elaborated using nanofabrication techniques.

We anticipate that the results of this exploratory project on magnon interferometry will be disseminated in several high-impact peer-reviewed journal articles, as well as being presented at international conferences.

1.4 Environment (partners, places, specific tools and hardware)

This research project will be articulated between four major activities: (i) the simulations and design of magnonic prototypes, (ii) the nanofabrication in a state-of-the-art facility, and (iii) the setup of the NV center microscope and (iv) the measurement of devices.

(i) In a first stage, the PhD candidate will carry out simulations at IMT Atlantique, implementing the near- field diffraction model for spin-wave to select suitable geometries for interferometric magnonic devices.

(ii) Following the selection of designs, the student will undertake nanofabrication missions at the STnano cleanroom facility at IPCMS to elaborate real devices. They will be primarily trained and supervised on e-beam and optical lithography, thin film deposition, and etching methods.

(iii) In parallel, the student will have several stays at Qnami, where they will develop a module with probing capacity integrable to Qnami commercialized NV microscopes.

(iv) Finally, the student will measure and analyze the scanning NV data, with a focus on identifying the role of nanoscale fabrication imperfections, and scattering sites on the overall device's performance.

1.5 Interdisciplinarity aspects

The proposed topics is a combination of several skilled tasks that the student will acquire and perform throughout his PhD project. It includes firstly some fundamental studies and simulations on spin wave dynamics, secondly the elaboration of magnonic devices using state-of-the-art nanofabrication equipment, and thirdly an engineering work in order to integrate a probing scheme with external applied field into Qnami commercialized NV microscopes.

1.6 References

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2 Partners and study periods

2.1 Supervisors and study periods

- **IMT Atlantique**: Assoc. Prof. Vincent Vlaminck, IMT Atlantique, Brest, France

  The PhD student will stay 2 years at Prof. Vlaminck's lab.

- **International partner**: Dr. Peter Rickhaus, Qnami, Basel, Switzerland

  The PhD student will stay 1 years at Dr. Rickhaus' lab.

2.2 Hosting organizations

2.2.1 IMT Atlantique

IMT Atlantique, internationally recognized for the quality of its research, is a leading French technological university under the supervision of the Ministry of Industry and Digital Technology. IMT Atlantique maintains privileged relationships with major national and international industrial partners, as well as with a dense network of SMEs, start-ups, and innovation networks. With 290 permanent staff, 2,200 students, including 300 doctoral students, IMT Atlantique produces 1,000 publications each year and raises 18€ million in research funds.

2.2.2 Qnami

Qnami AG, a 25-employee start-up company located in Basel (Switzerland), pioneer in scanning NV magnetometer. Generally, Qnami develops fundamental new technology using quantum mechanics. The control and measurement of the state of a single electron permits to measure what could never be measured before.